Statistical Ocean-Acoustics and Environmental Inversion After Stochastic Propagation and Scattering

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LONG-TERM GOAL

The long term goal of this research is to provide a unified statistical theory for ocean-acoustic measurements made after stochastic propagation and scattering that accounts for both the temporal and spatial coherence of the received field. Such a theory must be in place before acoustic measurements can be effectively used as a tool to either probe the marine environment or communicate and autonomously navigate within it. To understand why this is the case, one must first realize that for many diverse realizations of stochastic wave propagation in ocean-acoustics, from transmission through a fluctuating waveguide to reverberation from the oceanic boundaries or volume to acoustic imaging of submerged surfaces and objects, the field received by a sonar system is found to undergo statistical fluctuations even in the absence of additive noise. In stochastic propagation, these fluctuations are caused by natural disturbances in the marine environment such as turbulence or passing surface gravity and internal waves. In stochastic scattering, the fluctuations arise from slight variations in the volume inhomogeneities, surface roughness or object structure interrogated by the acoustic field.

Most inverse methods in ocean-acoustics, whether their purpose is to probe the marine environment, image or locate submerged objects, require the nonlinear inversion of fluctuating acoustic field data. However, the nonlinear inversion of this random data leads to inherent statistical biases and variances. These biases and variances are a significant problem because they not only depend upon the deterministic marine environmental or target parameter to be estimated, but also on the way the measurements are made and fluctuate. The goal is to develop a unified approach that couples the physics of ocean-acoustic propagation and scattering with the inherent statistical fluctuations of ocean-acoustic measurements to quantify biases and variances inherent in ocean-acoustic inverse problems and to set conditions on the statistical degrees of freedom required to insure that resulting marine parameter estimates are significant.

OBJECTIVES

The following three objectives drove the first year of this research program:

(A) The development of a practical physical model for scattering from objects and boundaries in a waveguide that elucidates the fundamental and unique characteristics of scattering in shallow-water.

(B) The development of a statistical model for partially saturated acoustic intensity measurements and their log-transforms that relates statistical degrees of freedom to the temporal coherence of the received field and its expected random and non-random components. This extends and generalizes previous work for completely saturated measurements [1, 2]. This generalization is significant because it encompasses all acoustic field measurements that can be described by a random Gaussian component

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with an additive deterministic signal. The random component may be either independent and additive, as ambient noise, or it may be multiplicative and signal-dependent as it is after stochastic propagation and scattering. This overall approach applies to many practical scenarios in ocean-acoustics as a consequence of the central limit theorem.

(C) Experimental determination of the primary issues in modeling bistatic seafloor reverberation in range-dependent environments.

A synthesis of the physical scattering models (A), statistical and coherence theory models (B) and experimentally determined bottom scattering models (C) is planned to meet the long term goals of the last section.

APPROACH

A unique approach is required for each of the three objectives.

(A) A spectral approach to 3-D object scattering in layered media by Makris et al [3] is applied to study the fundamental characteristics of scattering from objects [4] and boundaries [5] in a shallow water waveguide. This spectral approach has been rigorously derived from the exact Kirchoff scattering theory yet is extremely practical to implement since it is expressed as a linear function of the object's planewave scatter function. This simplification requires two conditions that are typically met in practice, namely (1) the scatterer is significantly far from the waveguide boundaries that *multiple scattering* between object and waveguide boundaries can be neglected and (2) the range from the object to the source or receiver is much greater than the object's spatial extent. Waveguide propagation to and from the object are fully accounted for since the waveguide Green function is used. Essential to this approach then is *multiple reflection* of the incident and single-scattered field from the waveguide boundaries, which leads to multiple images of the source and object if the method of images is invoked.

(B) Mathematical techniques are used to derive analytic expressions for the statistical degrees of freedom of partially saturated measurements in terms of their temporal coherence and the expected value of the deterministic and random components of fluctuating intensity. Analytic expressions are also derived for the probability distributions, moment generating functions and moments of finite-time-averaged intensity and log-transformed intensity as a function of the measurement degrees of freedom [6].

(C) High resolution bistatic images of a typical abyssal hill feature on the western flank of the Mid-Atlantic Ridge made with a low frequency towed-array system operating remotely at ½ convergence zone (CZ) stand-off during one of the bistatic scattering experiments designed by the present PI [7] for the ONR Special Research Program (SRP) are compared with modeled reverberation images generated from high resolution supporting bathymetry (sampled at the wavelength scale) and a synthesis of parabolic equation and raytrace techniques. Research vessel navigation, acoustic propagation to and from scattering sites on the abyssal hill and the projected area of the scattering sites with respect to the source and receiver propagation paths are modeled with wavelength-scale accuracy. To extract the bi-azimuthal scattering distribution function of the major scarps on the abyssal hill, the model assumes uniformly diffuse scattering [8, 9].

WORK COMPLETED

(A) The spectral formulation described above has been applied to elucidate the essential characteristics of 3-D scattering by potentially non-compact ($1<ka$) objects in shallow water from close proximity to the object out to arbitrarily large ranges. Primary attention is given to the important special case of scattering from a sphere in a layered medium. While the sphere shares many basic 3-D scattering characteristics with other objects, most important of which is the relative amplitude of forward scatter to other directions, it also has a solution that is practical to implement. Specifically, an analytic expression is derived for the 3-D field scattered from a sphere in a waveguide. The expression fully exploits separation of variables and so is given in terms of 1-D wavenumber integrals [4]. The expression also includes scattering of evanescent waves by analytic continuation. The spectral approach has also recently been extended to stochastically treat scattering from range-dependent seafloor features [5] by incorporating the lessons learned from the experimental reverberation analysis of (C).

(B) Closed-form and series solutions are provided for all the distributions, moments, generating functions and degrees of freedom listed in the approach, including general expressions for the bias of the sonar equation and the standard deviation of the logarithmic quantities commonly used in ocean-acoustics for the general case of a deterministic field combined with a Gaussian random field [6]. Accompanying curves are also computed. Simpler asymptotic expressions are also derived for various limiting cases.

(C) Reduction of bistatic scattering data from the B’ component of the SRP Main Acoustics Experiment has been completed. A combined parabolic-equation and raytrace-based reverberation approach has been developed to accurately model bistatic reverberation from the seafloor in deep water. The effective resolving power of a towed-array system in remotely imaging deep-ocean bathymetry has been experimentally determined. The bi-azimuthal scattering distribution function of a typical deep-ocean abyssal hill has been experimentally determined.

RESULTS

(A) Computations for a non-compact pressure-release sphere (a=10m) in a shallow water Pekeris waveguide (100 m depth) at 300 Hz illustrate the essential characteristics of 3-D object scattering in a shallow but multi-modal waveguide [4]. Relative to free-space scattering, a significant decrease in the level of the scattered field in the forward direction as well as a pronounced vertical beaming effect in the vicinity of the sphere are discovered. In the forward direction, the beaming effect can be easily interpreted in terms of the convolution of the highly directional incident field, where the trapped modes reveal themselves as narrow incident beams, with the forward diffraction lobe of the object that has angular width of roughly • /(2a). Another primary finding is that with increasing range the vertical structure, but not the horizontal, of the scattered field eventually converges to that of a monopole point source placed at the object centroid. This occurs when the angular spectrum of the scattered field has bandwidth on the order or less than • /(2a). In this case only a constant factor is available to classify the object. As a result, multistatic observations of the scattered field, distributed over an azimuthal aperture greatly in excess of • /(2a) will be necessary to classify objects submerged in shallow water at ranges exceeding the watercolumn depth. Finally, standard sonar equation analysis is found to overestimate the field scattered from non-compact objects in shallow water by tens of decibels and so is completely inappropriate although it is perhaps the most commonly used approach in shallow water active-sonar applications at the present time.

(B) The degrees of freedom for partially saturated measurements depend not only on the temporal coherence of the random component of the received field, but also on the spectral coefficient of the random component at the deterministic component's frequency, as well as the expected intensities of the random and deterministic field components. When the deterministic component is much larger than the random component, the degrees of freedom roughly equal the ratio of the measurement time to the spectral coefficient of the random field at the deterministic component's frequency. When the deterministic field has amplitude that is much smaller than the random field, the previously derived expressions for the fully saturated [1] degrees of freedom apply. For large degrees of freedom, intensity distributions and log-transformed intensity distributions are rigorously shown to obey the central limit theorem and so become asymptotically normal and lognormal respectively. The bias of the sonar equation attains its maximum value of • 2.5 dB and the standard deviation of log-transformed intensity measurements attains its maximum value of 5.6 dB when the degrees of freedom approach unity and the expected intensity of the random field is large compared to that of the deterministic, which is essentially the saturated single-degree-of-freedom case. Both the bias and standard deviation vanish when either the degrees of freedom are large or the random field component becomes small. The transitions from one extreme to the other, however, follow a very complicated functional dependence that is expressible in terms of sums of special functions. Asymptotic formulas are more handy than the exact expressions in the limiting cases.

(C) High resolution bistatic images of a typical abyssal hill on the western flank of the Mid-Atlantic Ridge made with a low-frequency towed-array system operating remotely at ½ CZ stand-off are compared with modeled images, generated from high resolution supporting bathymetry sampled at 5-m intervals, roughly the wavelength scale. The comparison reveals that steep scarps return the strongest echoes because they project the largest area along the acoustic path from the source to receiver. Prominent returns deterministically image scarp morphology when the cross-range resolution footprint of the system runs along the scarp axis. Statistical fluctuations inherent in the scattered field prevent the system from distinguishing smaller-scale anomalies on the scarps, such as canyons and gullies (~100-200 m scale), that would otherwise be resolvable in range in certain bistatic geometries. The mean bi-azimuthal scattering strength distributions of the two major scarps on the abyssal hill are *identical* and equal to the *constant* –17 dB +/• 8 dB. This suggests that long-range reverberation from prominent geomorphological features of the world's Mid-Ocean Ridges can be adequately modeled as Lambertian with albedo • $/10^{1.7}$, given supporting bathymetry sampled with sufficient frequency to resolve the projected area of these features [8, 9].

IMPACT/APPLICATIONS

(A) The spectral approach to 3-D object scattering in shallow water provides an accurate and practical tool for determining the level of active sonar returns from submerged objects in shallow water. Computations for a spherical object have led to many new discoveries about the unique characteristics of the field scattered from a non-compact object in a multi-modal waveguide that have no analogue in free-space scattering. For practical applications, sonar equation analysis is found to be optimistic by tens of decibels and is therefore inappropriate for non-compact object scattering in a multi-modal waveguide, although it is still the most common approach in shallow water active sonar applications. Also, multistatic observations of the scattered field, distributed over an azimuthal aperture greatly in excess of • $/(2a)$ will be necessary to classify objects submerged in shallow water at ranges exceeding the watercolumn depth.

(B) Most measurements made in ocean acoustics undergo fluctuations due to randomization of the signal during propagation or scattering or due to additive noise. By the central limit theorem, field fluctuations can very often be described by complex Gaussian random variables. The present statistical analysis is significant because it provides analytic expressions for the inherent biases and standard deviations of all decibel measures used in ocean acoustics when part of the measured field is random and the other part remains deterministic, which is the most general case. Decibel measures are widely used because they not only compress the dynamic range but are also statistically optimal due to their variance stabilizing properties [10].

(C) Long-range reverberation from range-dependent features of the world's seafloors can be adequately modeled as diffuse scatterers, given their acoustic albedo and supporting bathymetry sampled with sufficient frequency to resolve their projected area.

TRANSITIONS

The scattering theory and statistical results are now being used in collaboration with Douglas Cato of DSTO Australia to investigate passive localization of humpback whales using scattered signals from vocal whales and in analysis of buried mine data from the GOATS 98 experiment of Henrik Schmidt of MIT.

RELATED PROJECTS

There are no related projects for FY98, but there will be two for FY99, namely the SECNAV/CNO chair and scholar program and a new ONR program on scattering from fluctuating targets in a fluctuating waveguide.

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